MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

E463 – PROJECT #3

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I) INTRODUCTION

This report is prepared for the third software project of EE463 Fall2018 class in order to understand 3-Phase Thyristor Rectier and DC/DC Converter operation and characteristics. Throughout the project Turkish grid system which has $400V_{ll}$ and 50Hz operation is used.

First question investigates PI control of speed of a PM DC motor by controlling the firing angle of a three phase controlled rectifier as well as tuning of the PI controller and alternative driving methods for the DC motor. In the second question, designing and simulating a Buck converter using a power MOSFET are performed. Finally, in the last question, a step-up converter as known as boost converter is designed using WEBENCH, which is a digital platform created by Texas Instruments to design and simulate converters online.

II) QUESTIONS

QUESTION 1: 3-Phase Thyristor Converter

In this question our goal is to design a proportional-integral (PI) controller that makes the motor speed to follow the reference input speed change by changing the firing angle of a 3-phase thyristor converter. PI controller is used to reduce, or ideally eliminate, the steady-state error between the measured motor speed and reference speed. In Figure 1.1, the feedback control system is shown.

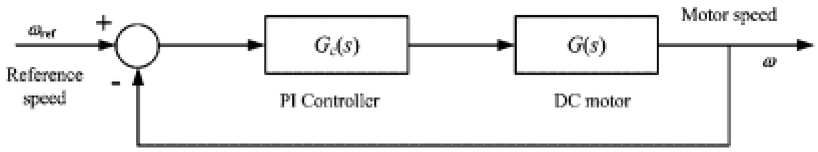

Figure 1.1: Closed loop feedback control system of DC motor

Transfer function of the PI controller is given by (1). To design a proper controller, the dynamics of the DC motor should be described by a transfer function as well. However, with the help of tuning application methods of Simulink that will not be necessary.

$$G_c(s) = K_p + \frac{K_i}{s} \qquad (1)$$

Feedback control system schematics can be seen in Figure 1.2, plant to be controlled is labeled as DC Motor. Inside the plant can be seen in Figure 1.3. Upper and lower limits for PI output are included as 90 and 0 to obtain positive voltage mean at the armature terminals.

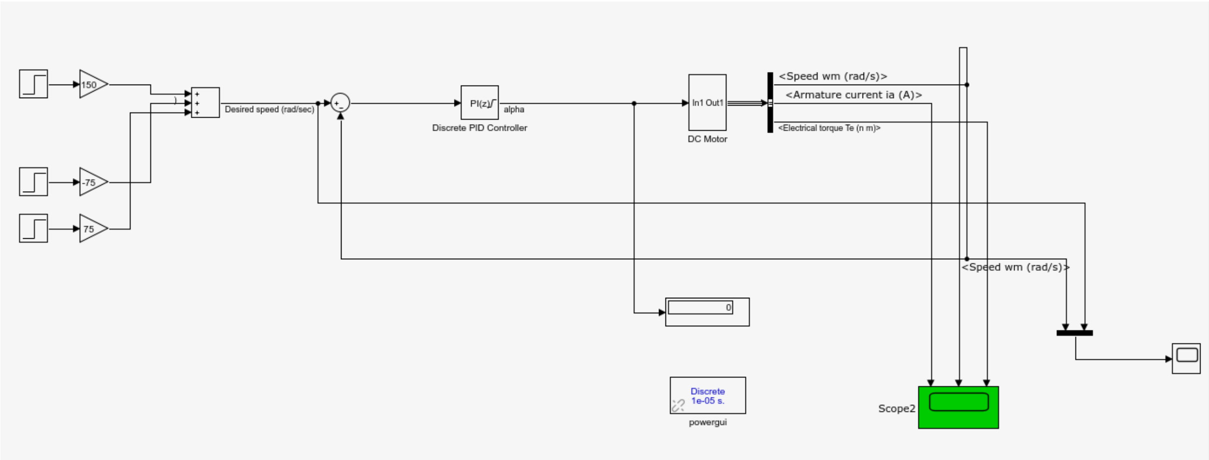

Figure 1.2: Feedback control system

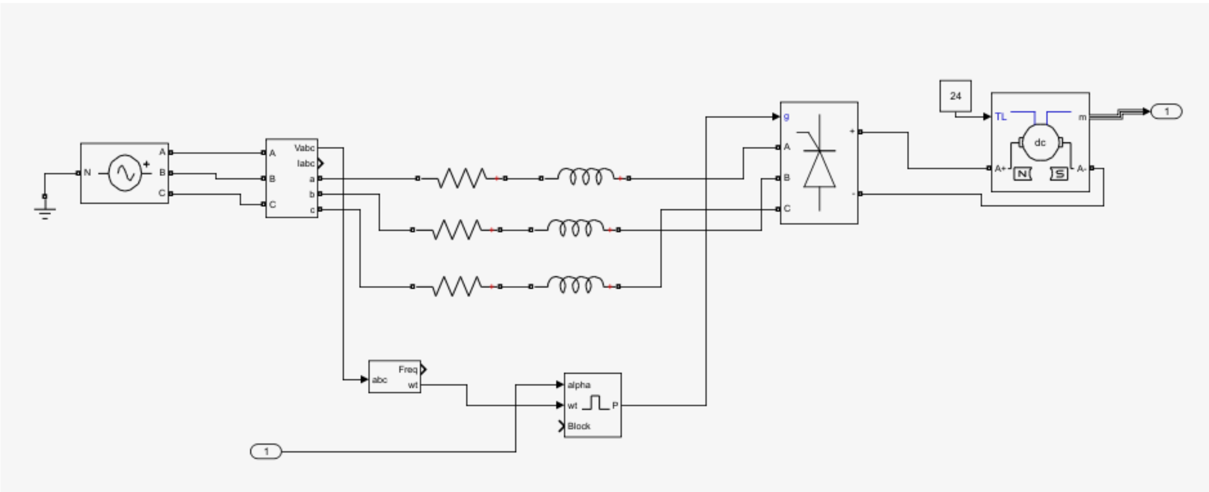

Figure 1.3: Inside the plant

To model the controller at first, we tried to use Transfer Function Based (PID Tuning) tuning method, which linearizes the plant, calculates PID gains, and opens GUI to adjust respond time however, we could not fix ‘’initial stabilizing controller” error that we received. Therefore; we used Frequency Response Based Tuning Method and found K_p and K_I as -2.0474 and -3.7927, respectively. Note that transfer function of the controller is a little different than (1), since it is a discrete time PID controller block. Motor speed and reference speed comparison can be seen in Figure 1.4, and armature current, speed and torque waveforms can be seen in Figure 1.5.

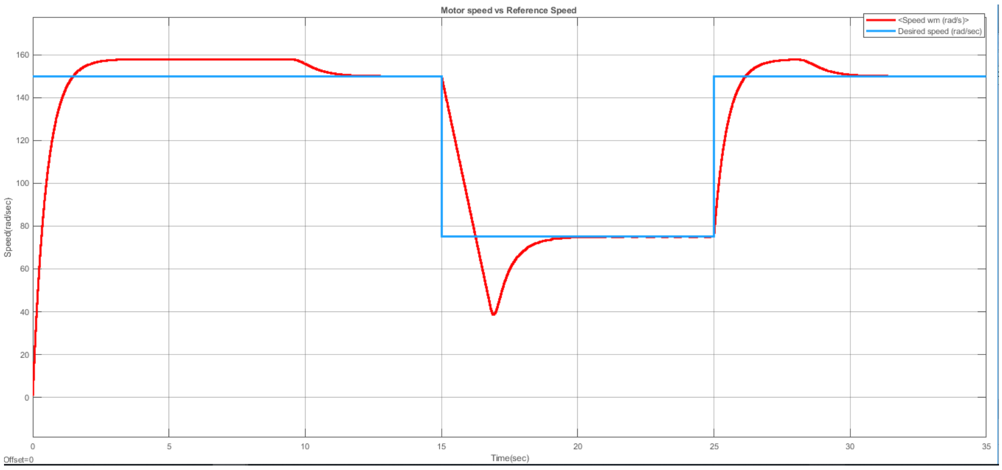

Figure 1.4: Reference and motor speed comparison

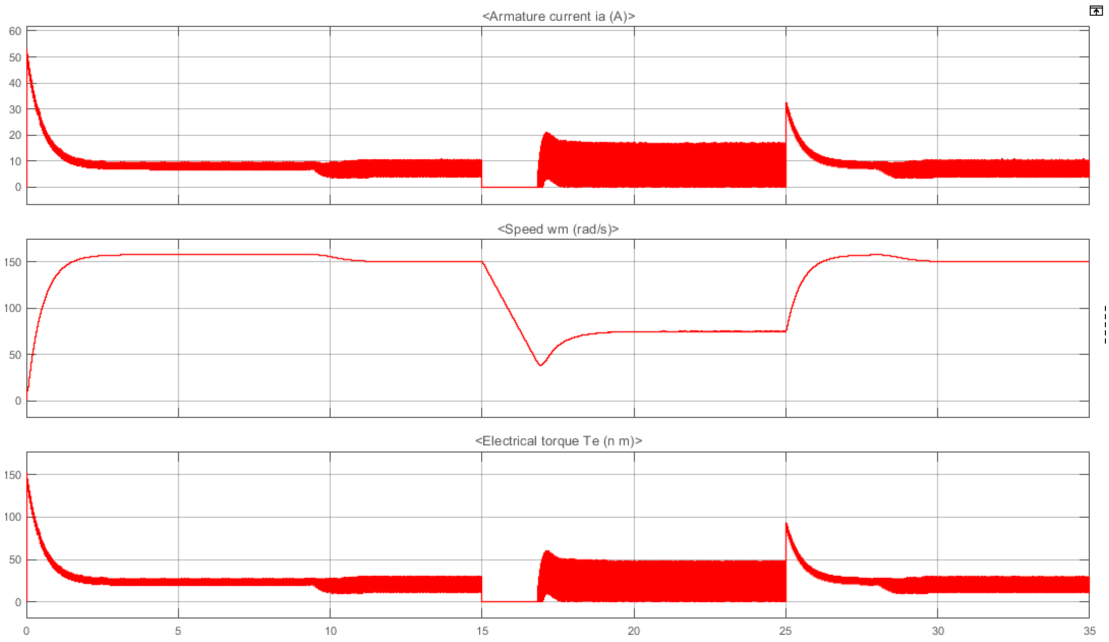

Figure 1.5: Armature current, speed and torque waveforms

From Figure 1.4-5 we can see that motor speed reaches zero steady state error eventually due to the integrator in the PI controller. We used various K_p and K_I values but the characteristics of these waveform did not change much. However, after only using P controller and PI controller we have figured out that with P controller we cannot reach zero steady state error and with PI controller any amount of K_I guarantees overshoot. Also, from Figure 1.5 we can see that torque waveform persuades armature current waveform oscillations as it was observed in Project 2 as well.

In Figure 1.4 we can see that motor takes some time to decrease its speed to 150 rad/sec from 157 rad/sec when we first start the motor. Changing K_p and K_I values did not help this problem. However, using a different driving technique by gradually increasing the reference speed from zero to 150 rad/sec decreases the starting time from 12 seconds to 8 seconds as it can be seen from Figure 1.6. Armature current, speed and torque waveforms again repeated for this driving technique in Figure 1.7.

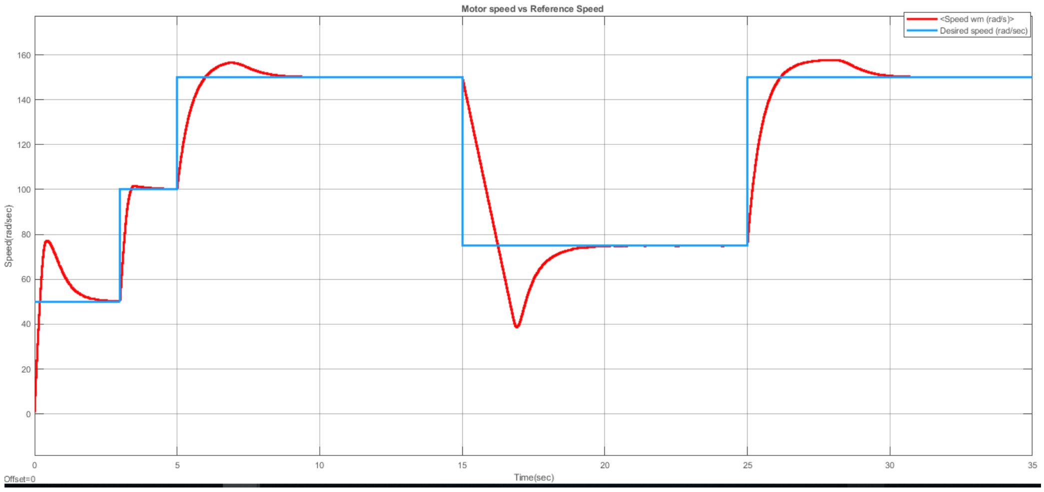

Figure 1.6: Reference and motor speed comparison

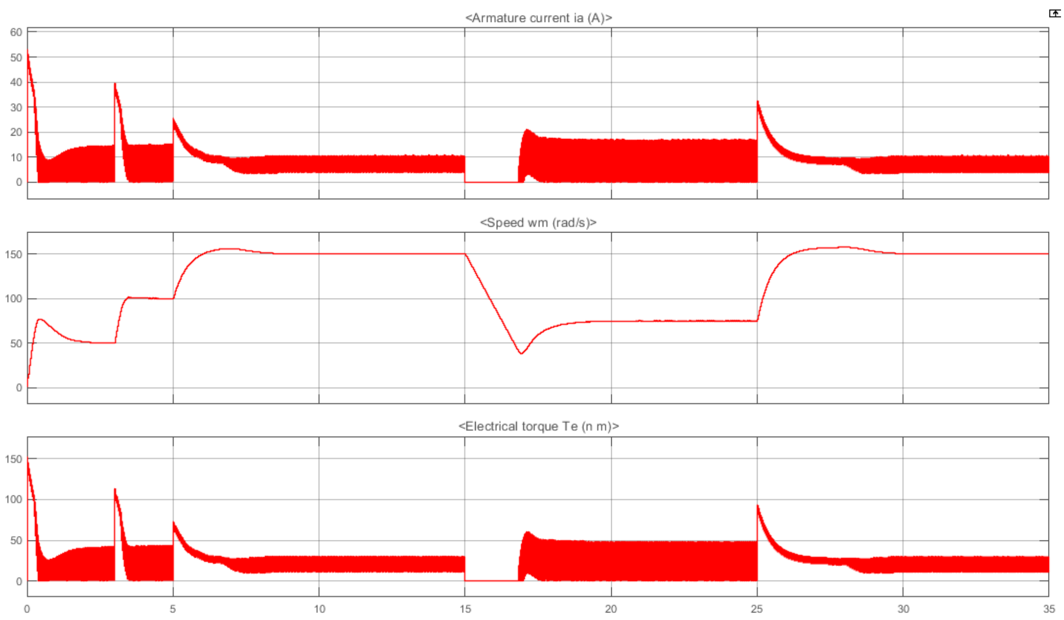

Figure 1.7: Armature current, speed and torque waveforms

QUESTION 2: Buck Converter

In this part of the project we are asked to design a buck converter. To achieve successful operation we need determine values of switching frequency and commercially available circuit elements. Let's begin with using;

$V_{in} \times D = V_{out}$, Since we know input and output voltages. Duty ratio is found 0.5. For D=0.5 we know that;

$I_{out} / I_{LB,\,max} > 1$ so that we can avoid being at discontinuous conduction mode. Since

$I_{LB, max} = T_s \times V_{in} / 8 \times L$ putting know values into this equation we found;

$L / T_s > 1$ or $L \times f_s > 1$

After finding this final relationship we can determine switching frequency and inductance value. In order not to select too big inductor we select f_s=20 kHz. Selected inductor and its parameters listed in Table 2.1.

Table 2.1: Selected inductor and its parameters

Product code	IHB5EB331K
Datasheet	http://www.vishay.com/docs/34015/ihb.pdf
Inductance	330 µH
Current Rating	7.3 A
DCR	49 mOhm (max)
Price	$16.99625

Note that altough we can select an inductor with smaller inductance value we select an inductor with highest possible inductance value that meets our criteria. Reasons is with higher inductances we can get lower Δi_L so that we can have lower output voltage ripple.

$\Delta V_{out} / V_{out} = \pi^2 \times (1\text{-}D) \times (f_c / f_s) / 2$

Considering voltage ripple and corner frequency should be much smaller than switching frequency a capacitor is selected. Capacitor product code and its parameters are listed in Table 2.2.

Table 2.2: Selected capacitor and its parameters

Product code	EGXF350ELL751MU15S
Datasheet	http://www.chemi-con.co.jp/cgi-
Capacitance	750 µF
Voltage-Rated	35 V
ESR	67 mOhm (@100kHz)
Price	$0.81218

Selected MOSFET is and its parameters also included in Table 2.3.

Table 2.3: Selected MOSFET and technical properties of it

Product code	FDS5680
Datasheet	https://www.fairchildsemi.com/datasheets/FD/FDS5680.pdf
Drain-Source Voltage	60 V
Gate-Source Voltage	-+20 V
Continuous drain current	8 A
Pulsed drain current	50 A
Power dissipation	2.5 W
Price	$1.86000

In our application maximum drain current is 43 A for few milliseconds, thus selected MOSFET meets that requirement too.

Lastly diode product code and its parameters indicated in Table 2.4.

Table 2.4: Selected diode and its parameters

Product code	MBR860MFS
Datasheet	https://www.onsemi.com/pub/Collateral/MBR860MFS-D.PDF
Peak Repetitive Reverse Voltage	60 V
Average forward current	8 A
Peak surge current	150 A
Forward Voltage	0.8 V
Price	$0.80000

After selecting all components Buck converter is simulated in Simulink and resulted steady state graphs indicated in Figure 2.1 and Figure 2.2.

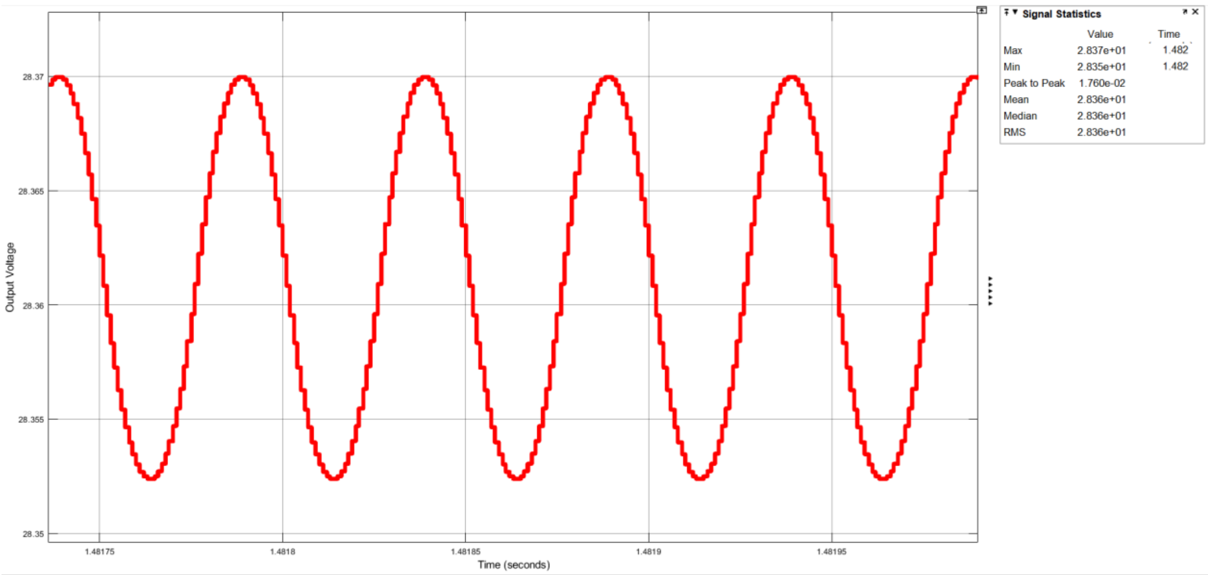

Figure 2.1: Output voltage at steady state

As seen in Figure 2.1 $\Delta V_{out} = 0.0176$ V which is low enough for us.

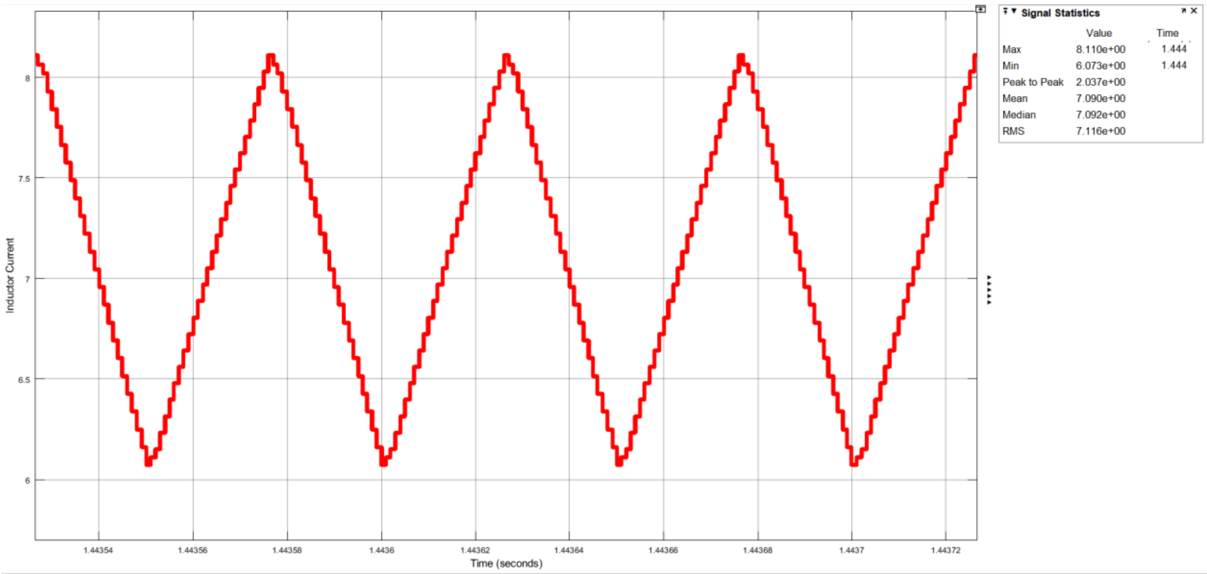

Figure 2.2: Inductor current at steady state

As seen in Figure 2.2 ΔI_L = 2.037 A which is again low enough for us. Lastly we need to add non-idealities to our converter from components that we selected and then determine the efficiency of the converter. For this after add non-idealities from datasheets of components we found input and output average powers which is shown in Figure 2.3.

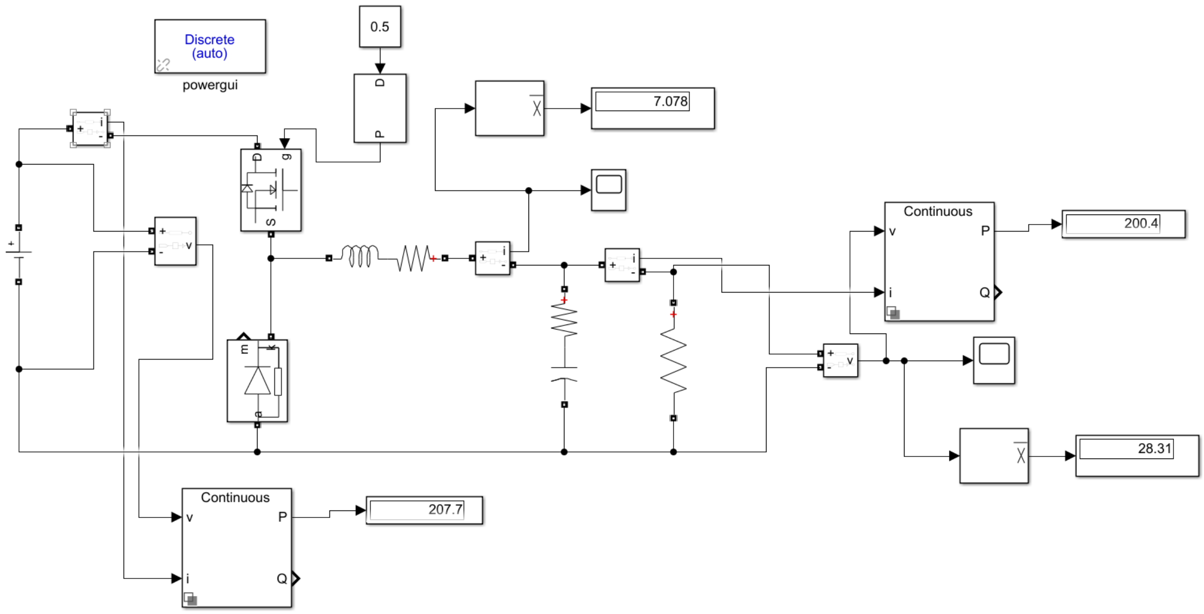

Figure 2.3: Input and output average powers

From this efficiency of converter = % 96.49

Overall cost = $20.46843

At the end our converter is rather expensive but efficient. Efficiency of converter affected by switching and conduction losses at MOSFET and diode mainly and DCR and ESR values of inductor and capacitor is also effects the efficiency. Switching and conduction losses of the semiconductor devices are affected by switching frequency and their own parameters. When we include their parameters that made them non-ideal, we found the efficiency value. Note that although we add DCR and ESR values as well, they have not so much effect.

QUESTION 3: Boost Converter (Webench)

In this question we are expected to design a boost converter, whose parameters are given in Table 3.1, using WEBENCH.

Table 3.1: Parameters of the step-up converter:

Vin	5± 0.2 V
Vout	12 V
Pout	24 W
Tamb	25 C

3.1) Design Strategy:

We are expected to design a commercial product; therefore, the first consideration should be the BOM cost, which is the cost of comprehensive inventory of the raw materials, assemblies, subassemblies, parts and components, as well as the quantities of each, needed to manufacture a product. [1]. Secondly personally, footprint of the material is a crucial point. Finally, efficiency of the material should be as high as possible. WEBENCH Optimizer in Figure 3.1, presents 5 optimizing options. Using the order of importance of considerations, we explained above, we chose the second optimizing option as it can be seen from Figure 3.1 as well.

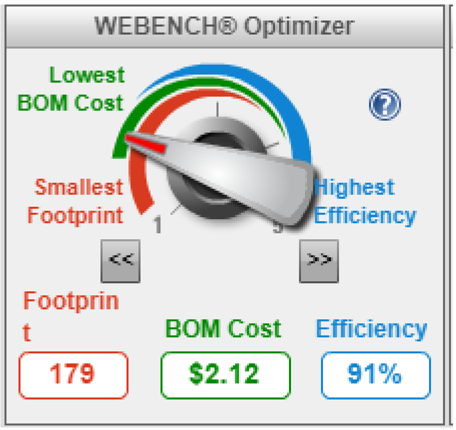

Figure 3.1: WEBENCH Optimizer

Using the optimizer and input parameters in Table 3.1, Advance Charting filters converters for us. In Figure 3.2, Advance Charting plot for our design can be seen, sizes of bubbles correspond to costs of converters, X axis is efficiency and Y axis is footprint. According to the chart, the bubble with the smallest size and closest to right bottom is the optimum converter. This converter is indicated with green. For our design, TPS61088 is selected.

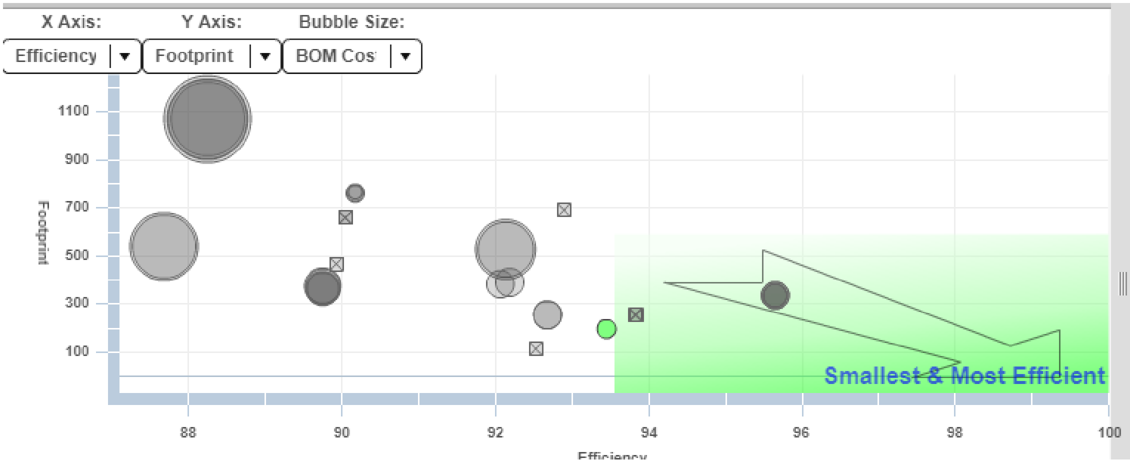

Figure 3.2: Advance Charting of converters

3.2) Most Advantageous Solution: TPS61088

After finding a design we are asked to record circuit schematic, Efficiency vs. output graph and output voltage ripple vs. Output current graph which are indicated in Figure 3.3, Figure 3.4 and Figure 3.5 respectively.

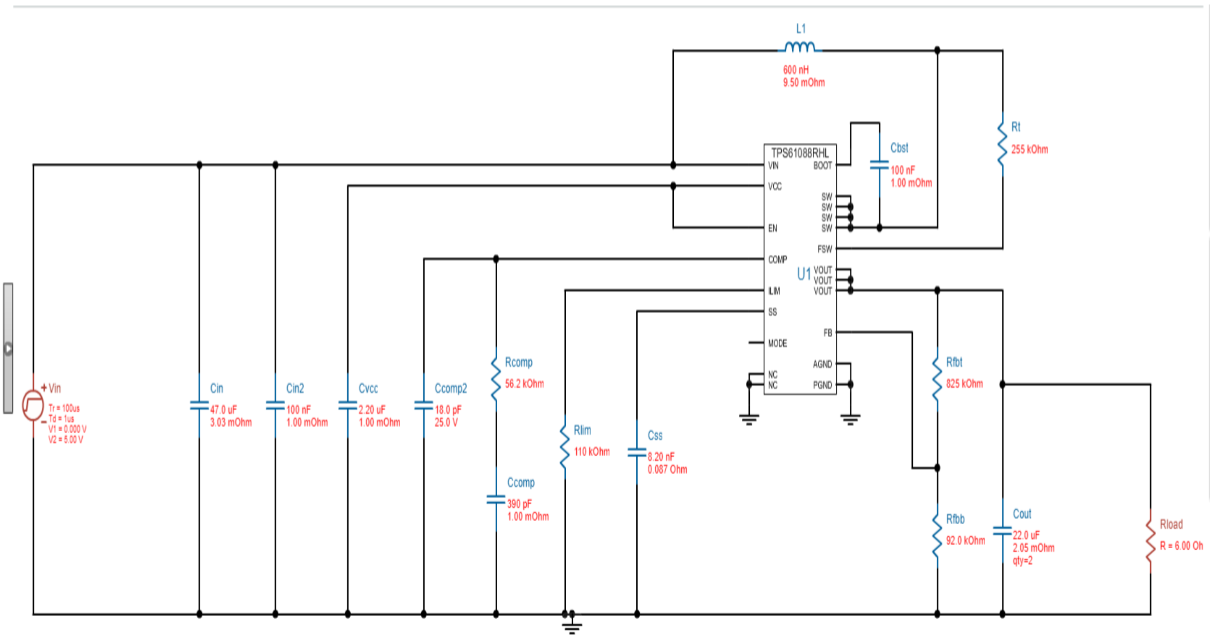

Figure 3.3: Circuit schematic of the selected design

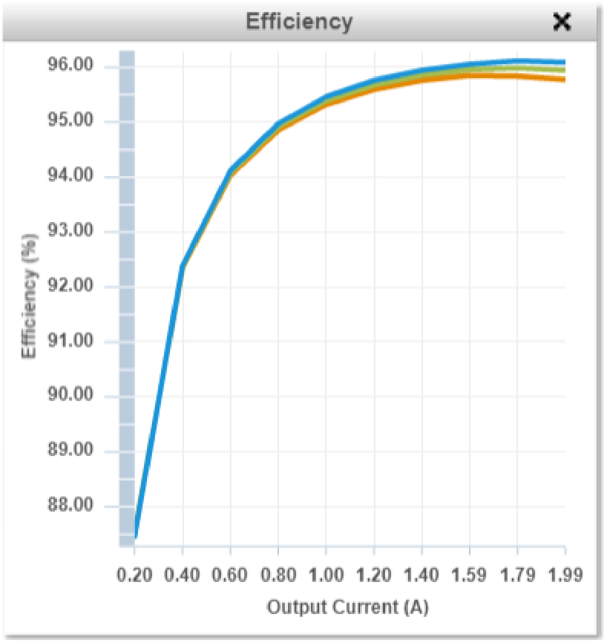

Figure 3.4: Efficiency vs. output current graph

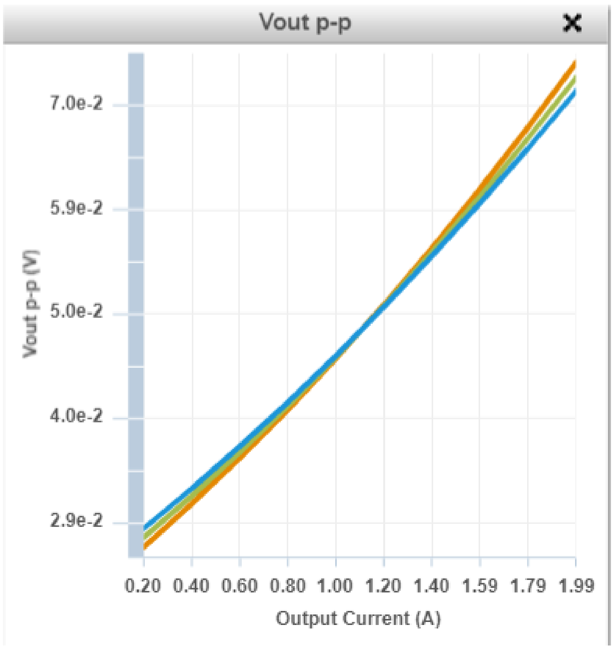

Figure 3.5: Output voltage ripple vs. output current graph

According to Figure 3.4, if we use this converter with light loads (Higher currents are drawn.), it is more efficient however according to Figure 3.5, this time output voltage ripple increases. Overall, as output current decreases, efficiency and output voltage ripple decreases as well.

Important parameters are listed in Table 3.2 and power loss graph for circuit elements indicated in Figure 3.6. According to the power loss graph, most of the losses are due to IC and inductor but inductor losses have also significant percentage. However, input and output capacitor's power dissipation are negligible.

Table 3.2: Design operating values

Inductor current peak to peak value	8.204 A
Output voltage peak to peak value	0.074 V
Efficiency	95.78 %
IC junction Temperature	53.3°C
Mode	BOOST CCM
Footprint	123 mm^2
BOM cost	3.53 $

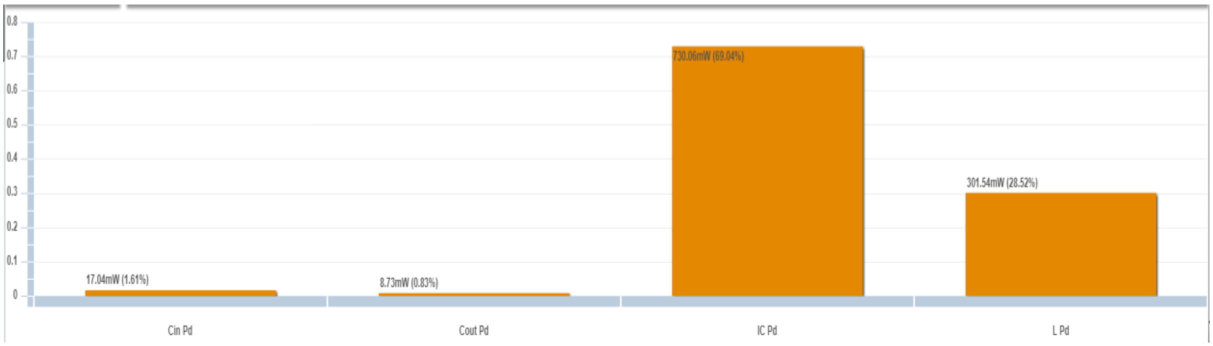

Figure 3.6: Power loss graph of circuit elements

Lastly, we were required to perform simulations and show their results. Simulations that are asked namely output voltage vs. time graph for steady-state, inductor current vs. time for steady-state, and output voltage & output current vs. time for load transient which are indicated in Figure 3.7, Figure 3.8 and Figure 3.9, respectively.

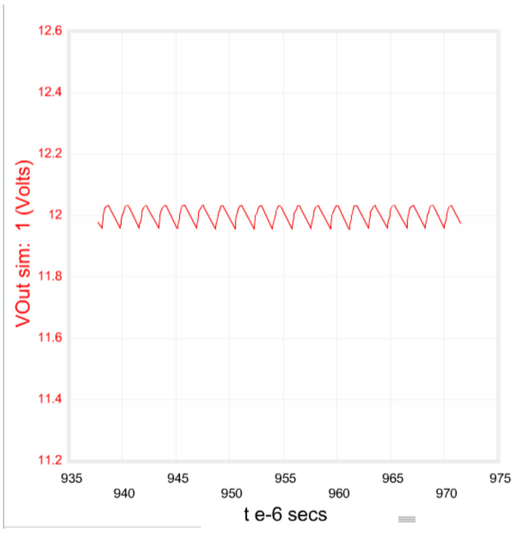

Figure 3.7: Output voltage vs. time simulation result for steady-state

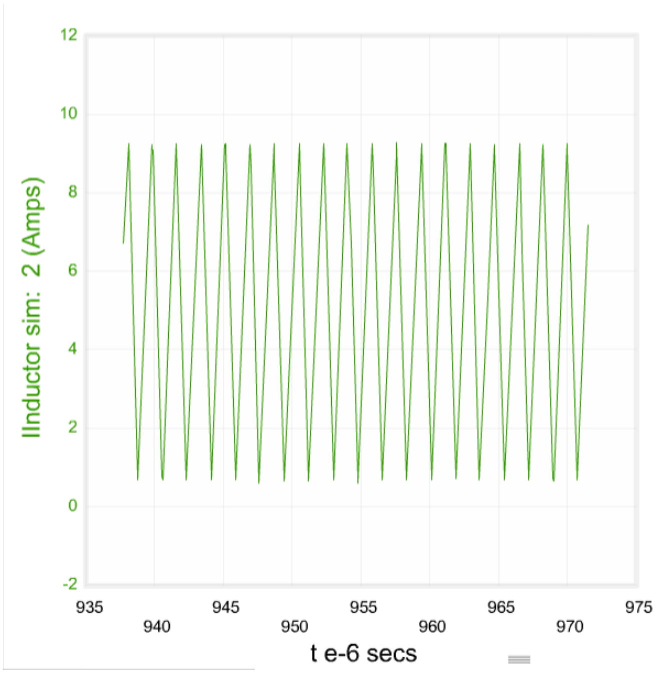

Figure 3.8: Inductor current vs. time simulation result for steady-state

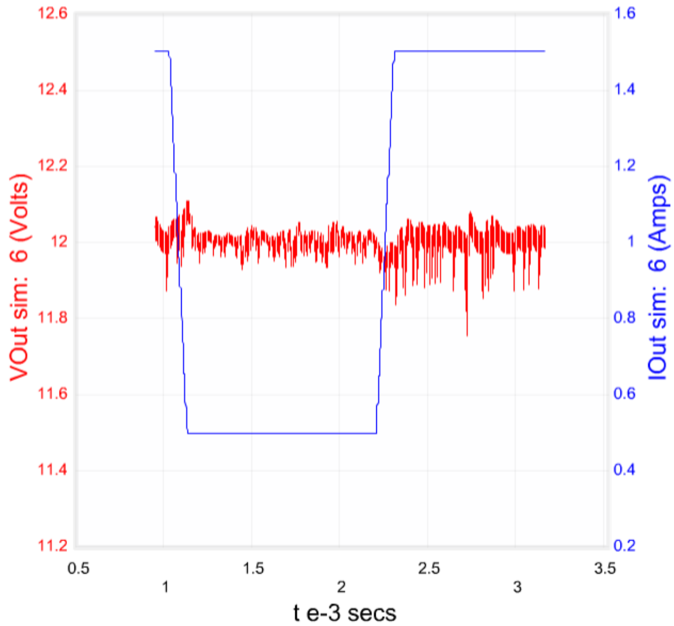

Figure 3.9: Output voltage (red) & output current (blue) vs. time for load transient

In Figure 3.7, we can see that output voltage ripple is pretty small, this is due to the low pass filter. In Figure 3.8, we can see linear increases and decreases in inductor current between the on/off states of the converter. Finally, according to the transient load response in Figure 3.9 if we ignore the outliers in the oscillations, we can see that while the load current changing there are only small overshoots in the output voltage response. Also, similar to what we have observed in Figure 3.5, there are greater outliers when output current is bigger.

III) CONCLUSION

In this project, controlling motor speed of a PM DC motor that is fed from a three-phase grid via a three-phase full bridge (fully controlled) thyristor rectifier is investigated in the first question. As controller a PI controller is used and tuning parameters of this controller is achieved via Frequency Response Based Tuning Method of Simulink. It is observed that with P controller one cannot reach zero steady state error and with PI controller any amount of K_I guarantees overshoot. Also, by gradually increasing the reference speed from zero to rated speed, a faster respond can be achieved.

In the second question, a buck converter is designed with commercially available circuit elements. At the end of the solution the designed converter is rather expensive but efficient.

Finally, in the last question a boost converter is designed to get the students familiar with the straight forward design method which is commonly preferred in industry using WEBENCH. A design strategy is formed and a commercially available converter is selected using Advanced Charting. Then, characteristics of this converter are observed. Main purpose of this question was to use Advanced Charting, Open Design, Op Vals, and Simulation sections of WEBENCH.

References

[1] https://searcherp.techtarget.com/definition/bill-of-materials-BoM